# Magnetic and axial-vector transitions of the baryon antidecuplet

Hyun-Chul Kɪᴍ[1,*], Ghil-Seok Yᴀɴɢ[2,**] and Klaus Gᴏᴇᴋᴇ[2,***]

[1] *Department of Physics, and Nuclear Physics & Radiation Technology Institute (NuRI), Pusan National University, 609-735 Busan, Republic of Korea*
[2] *Institut für Theoretische Physik II, Ruhr-Universität Bochum, D–44780 Bochum, Germany*

We report the recent results of the magnetic transitions and axial-vector transitions of the baryon antidecuplet within the framework of the chiral quark-soliton model. The dynamical model parameters are fixed by experimental data for the magnetic moments of the baryon octet, for the hyperon semileptonic decay constants, and for the singlet axial-vector constant. The transition magnetic moments $\mu_{\Lambda\Sigma}$ and $\mu_{N\Delta}$ are well reproduced and other octet-decuplet and octet-antidecuplet transitions are predicted. In particular, the present calculation of $\mu_{\Sigma\Sigma^*}$ is found to be below the upper bound $0.82\mu_N$ that the SELEX collaboration measured very recently. The results explains consistently the recent findings of a new $N^*$ resonance from the GRAAL and Tohoku LNS group. We also obtain the transition axial-vector constants for the $\Theta^+ \to KN$ from which the decay width of the $\Theta^+$ pentaquark baryon is determined as a function of the pion-nucleon sigma term $\Sigma_{\pi N}$. We investigate the dependence of the decay width of the $\Theta^+$ on the $g_A^{(0)}$, with the $g_A^{(0)}$ varied within the range of the experimental uncertainty. We show that a small decay width of the $\Theta^+ \to KN$, i.e. $\Gamma_{\Theta KN} \leq 1$ MeV, is compatible with the values of all known semileptonic decays with the generally accepted value of $g_A^{(0)} \approx 0.3$ for the proton.

## §1. Introduction

We would like to begin the present talk by mentioning about two Japanese physicists who were Yukawa's students and collaborators in 1940's. Shoichi Sakata and Mitsuo Taketani developed the three-stages theory based on a Marxist dialectical philosophy to explain how science is advanced.

*"Suppose a researcher discovers a new, inexplicable phenomenon. First he or she learns the details and tries to discern regularities. Next the scientist comes up with a qualitative model to explain the patterns and finally developes a precise mathematical theory that subsumes the model. But another discovery soon forces the process to repeat. As a result, the history of science resembles a spiral, going round in circles yet always advancing."*[1]

Since the first experimental observation of a signal of the pentaquark baryon $\Theta^+$ by the LEPS collaboration at SPring-8[2] which was triggered by the theoretical predictions from the chiral soliton model ($\chi$SM),[3] there has been a great amount of experimental and theoretical efforts to understand the nature of this new resonance $\Theta^+$. However, the null results of the recent CLAS experiment have cast doubt on

typeset using $\mathcal{PTP}$TEX.cls ⟨Ver.0.9⟩

its existence.[4]  Meanwhile, the DIANA collaboration has continued to search for the $\Theta^+$ and announced very recently the formation of a narrow $pK^0$ peak with mass of $1537 \pm 2$ MeV/$c^2$ and width of $\Gamma = 0.36 \pm 0.11$ MeV in the $K^+n \to K^0p$ reaction.[5]  Moreover, several new experiments for the $\Theta^+$ are under way.[6]–[8]  In the present cloudy status for the $\Theta^+$, more efforts are required for understanding the $\Theta^+$ theoretically as well as experimentally. No matter whether the $\Theta^+$ exists or not, such efforts will surely not end up in vain, as Sakata and Taketani put forward.[1]

In addition to the $\Theta^+$, the GRAAL collaboration[9],[10] and the Tohoku LNS group[11] announced the evidence of a new nucleon-like resonance with a narrow decay width $\sim 10$ MeV and a mass $\sim 1675$ MeV in the $\eta$-photoproduction from the neutron target. This new nucleon-like resonance, $N^*(1675)$, may be regarded as a non-strange pentaquark because of its narrow decay width and dominant excitation on the neutron target which are known to be characteristic for typical pentaquark baryons.[12]  Moreover, several theoretical calculations of the $\gamma N \to \eta N$ reaction[14],[15] support the identification of the $N^*(1675)$ as a member of the baryon antidecuplet, based on the values of the transition magnetic moments in Refs.[13],[16]

In the present talk, we would like to report recent investigations on the magnetic and axial-vector transitions of the baryon antidecuplet within the framework of the chiral quark-soliton model,[13],[17] emphasizing in particular the $\Theta^+$ and $N^*_{\overline{10}}$. We include the effects of flavor SU(3) symmetry breaking and employ the "*model-independent approach*"[18] in which all dynamical parameters of the model are fixed by existing experimental data.

## §2.  Formalism

The electromagnetic and axial-vector transition form factors are defined by the following transition matrix elements of the vector and axial-vector currents:[13]

$$\langle B|V_\mu^Q|B\rangle = \bar{u}_B(p_2)\left[F_1(q^2)\gamma_\mu + \frac{iF_2(q^2)}{M_1}\sigma_{\mu\nu}q^\nu + \frac{F_3(q^2)}{M_1}q_\mu\right]u_B(p_1),$$

$$\langle B_2|A_\mu^X|B_1\rangle = \bar{u}_{B_2}(p_2)\left[g_1(q^2)\gamma_\mu - \frac{ig_2(q^2)}{M_1}\sigma_{\mu\nu}q^\nu + \frac{g_3(q^2)}{M_1}q_\mu\right]\gamma_5 u_{B_1}(p_1), \quad (2\cdot1)$$

where the vector and axial-vector currents are defined as

$$V_\mu^Q = \bar{\psi}(x)\gamma_\mu\lambda_Q\psi(x), \quad A_\mu^X = \bar{\psi}(x)\gamma_\mu\gamma_5\lambda_X\psi(x) \tag{2·2}$$

with $Q = \frac{1}{2}(3 + 8/\sqrt{3})$ for the electromagnetic currents and $X = \frac{1}{2}(1 \pm i2)$ for strangeness conserving $\Delta S = 0$ currents and $X = \frac{1}{2}(4 \pm i5)$ for $|\Delta S| = 1$. The $q^2 = -Q^2$ stands for the square of the momentum transfer $q = p_2 - p_1$. The form factors $F_i$ and $g_i$ are real quantities due to $CP$-invariance, depending only on the square of the momentum transfer, among which we are mostly interested in $F_2$ and $g_1$. Taking into account the $1/N_c$ rotational and $m_s$ corrections, we can write the resulting magnetic moments $\mu^{(B)}$ and axial-vector constants $g_1^{(B_1 \to B_2)}(0)$ as follows:

$$\mu^{(B)} = w_1\langle B|D_{Q3}^{(8)}|B\rangle + w_2 d_{pq3}\langle B|D_{Qp}^{(8)}\hat{J}_q|B\rangle + \frac{a_3}{\sqrt{3}}\langle B|D_{Q8}^{(8)}\hat{J}_3|B\rangle$$

$$+ m_s \left[ \frac{w_4}{\sqrt{3}} d_{pq3} \langle B | D^{(8)}_{Qp} D^{(8)}_{8q} | B \rangle + w_5 \langle B | \left( D^{(8)}_{Q3} D^{(8)}_{88} + D^{(8)}_{Q8} D^{(8)}_{83} \right) | B \rangle \right.$$

$$\left. + w_6 \langle B | \left( D^{(8)}_{Q3} D^{(8)}_{88} - D^{(8)}_{Q8} D^{(8)}_{83} \right) | B \rangle \right],$$

$$g_1^{(B_1 \to B_2)}(0) = a_1 \langle B_2 | D^{(8)}_{X3} | B_1 \rangle + a_2 d_{pq3} \langle B_2 | D^{(8)}_{Xp} \hat{J}_q | B_1 \rangle + \frac{a_3}{\sqrt{3}} \langle B_2 | D^{(8)}_{X8} \hat{J}_3 | B_1 \rangle$$

$$+ m_s \left[ \frac{a_4}{\sqrt{3}} d_{pq3} \langle B_2 | D^{(8)}_{Xp} D^{(8)}_{8q} | B_1 \rangle + a_5 \langle B_2 | \left( D^{(8)}_{X3} D^{(8)}_{88} + D^{(8)}_{X8} D^{(8)}_{83} \right) | B_1 \rangle \right.$$

$$\left. + a_6 \langle B_2 | \left( D^{(8)}_{X3} D^{(8)}_{88} - D^{(8)}_{X8} D^{(8)}_{83} \right) | B_1 \rangle \right], \tag{2·3}$$

where $w_i$ and $a_i$ denote parameters encoding the specific dynamics of the chiral quark-soliton model. $\hat{J}_q$ ($\hat{J}_3$) stand for the $q$-th (third) components of the collective spin operator of the baryons, respectively. The $D^{(\mathcal{R})}_{ab}$ denote the SU(3) Wigner matrices in representation $\mathcal{R}$. The dynamical parameters $w_i$ and $a_i$ are fixed by the experimental data for the baryon magnetic moments, and hyperon semileptonic decay constants and singlet axial-vector constant of the proton, respectively. The magnetic moments of the baryon decuplet have been obtained in Ref.,[19] where those of the $\Delta$ and $\Omega$ baryons were well reproduced. Having obtained the numerical results of $w_i$ and $a_i$, we can immediately obtain the transition magnetic moments and axial-vector constants from the baryon octet to the antidecuplet.

## §3. Results and discussion

In Table I, we list the numerical results for the transition magnetic moments of the nonexotic and exotic baryons for three different values of the $\Sigma_{\pi N}$ in units of $\mu_N$. Those for $\mu_{N\Delta}$ and $\mu_{\Lambda^0 \Sigma^0}$ are in a very good agreement with the experimental and

| $\Sigma_{\pi N}$ [MeV] | $\mu_{N\Delta}$ | $\mu_{\Lambda^0 \Sigma^0}$ | $\mu_{\Sigma^- \Sigma^{*-}}$ | $\mu_{pp^*_{\overline{10}}}$ | $\mu_{nn^*_{\overline{10}}}$ | $\Gamma_{pp^*_{\overline{10}}}$ | $\Gamma_{nn^*_{\overline{10}}}$ | $\Gamma_{nn^*_{\overline{10}}}/\Gamma_{pp^*_{\overline{10}}}$ |
|---|---|---|---|---|---|---|---|---|
| 50 | $-3.06$ | 1.54 | $-0.44$ | 0.12 | 0.56 | 11.5 | 250 | 21.67 |
| 60 | $-3.16$ | 1.58 | $-0.50$ | 0.08 | 0.33 | 5.12 | 87.2 | 17.02 |
| 70 | $-3.31$ | 1.64 | $-0.59$ | 0.04 | 0.11 | 1.28 | 9.69 | 7.56 |

Table I. Transition magnetic moments in units of $\mu_N$. The experimental value for $\mu_{\Lambda^0 \Sigma^0}$ is given as $(1.61 \pm 0.08)\,\mu_N$. The empirical value for $|\mu_{N\Delta}|$ is approximately equal to $3.1\,\mu_N$. Partial decay widths $\Gamma_{NN^*_{\overline{10}}}$ for the radiative decays of exotic and nonexotic baryons in units of keV. The last column stands for the ratio of the partial decay widths $n^*_{\overline{10}} \to n + \gamma$ and $p^*_{\overline{10}} \to p + \gamma$.

empirical data.[13] The upper bound for $|\mu_{\Sigma^- \Sigma^{*-}}|$ extracted from the upper limit for the partial decay width of the SELEX experiment is around $0.82\,\mu_N$.[20] The present prediction for $\mu_{\Sigma^- \Sigma^{*-}}$ lies definitely in the allowed region for all reasonable values of $\Sigma_{\pi N}$. The $N^*_{\overline{10}} \to N$ transition magnetic moments are rather sensitive to the $\Sigma_{\pi N}$. It is very similar to the case of the magnetic moments of the baryon antidecuplet.[19] The reason is due to the fact that $\mu_{NN^*_{\overline{10}}}$ is proportional to $w_1 + w_2 + \frac{1}{2}w_3$, so that the terms with the $\Sigma_{\pi N}$ in $w_1$ and $w_2$ interfere linearly. As a result, $\mu_{nn^*_{\overline{10}}}$ decreases monotonically as $\Sigma_{\pi N}$ increases, as shown in Fig. 1.

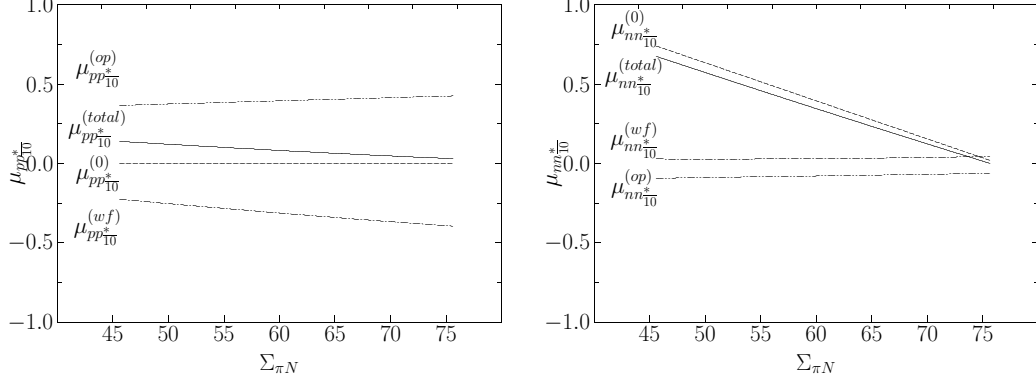Since the $p^* \to p$ transition one is SU(3) forbidden, it is rather small. More

Fig. 1.  $p^* \to p$ transition magnetic moment as functions of $\Sigma_{\pi N}$ in the left panel and $n^* \to n$ one
as functions of $\Sigma_{\pi N}$ in the right panel.

interestingly, the neutron transition magnetic moment is about three to five times
larger than the proton one. The partial width of radiative decays from the baryon
antidecuplet to the octet is expressed as

$$\Gamma(B_{\overline{10}} \to B_8 \gamma) = 4\alpha_{\rm EM} \frac{E_\gamma^3}{(M_8 + M_{\overline{10}})^2} \left(\frac{\mu_{B_8 B_{\overline{10}}}}{\mu_N}\right)^2, \tag{3.1}$$

where $\alpha_{\rm EM}$ denotes the fine structure constant and $E_\gamma$ is the energy of the produced
photon:

$$E_\gamma = \frac{M_{10(\overline{10})}^2 - M_8^2}{2M_{10(\overline{10})}}. \tag{3.2}$$

Since the partial decay width $\Gamma_{nn_{\overline{10}}^*}$ is proportional to the transition magnetic mo-
ment as shown in Eq.(3.2), it turns out to be about eight to twenty times larger
than $\Gamma_{pp_{\overline{10}}^*}$. This result is consistent with those of the GRAAL and Tohoku experi-
ments.[10],[11]

In Fig. 2, the transition axial-vector coupling constant for $\Theta^+ \to K^+ n$ is drawn
as a function of $\Sigma_{\pi N}$, three different values of the singlet axial-vector constant $g_A^{(0)}$ for
the proton being varied from 0.2 to 0.4. The larger $g_A^{(0)}$ we use, the smaller $g_A^{*(\Theta \to n)}$
we obtain. When $g_A^{(0)}$ is larger than 0.37, the $g_A^{*(\Theta \to n)}$ becomes even negative.

Since the decay width of the $\Theta^+ \to KN$ is proportional to the square of the
transition axial-vector constant as follows:

$$\Gamma_{\Theta KN} = 2\Gamma_{\Theta K^+ n} = \frac{\left(g_A^{*(\Theta \to n)}\right)^2 |\vec{p}|}{16\pi f_K^2 M_\Theta^2} \left[(M_\Theta - M_N)^2 - m_K^2\right](M_\Theta + M_N)^2, \tag{3.3}$$

it is rather sensitive to the $g_A^{*(\Theta \to n)}$. In Table II, we list the numerical results of the
the decay width of the $\Theta^+ \to KN$, $\Gamma_{\Theta KN}^{\rm total}$ for four different values of the $g_A^{(0)}$ as a
function of $\Sigma_{\pi N}$. The $\Gamma_{\Theta KN}^{\rm total}$ turns out to be the smallest with $g_A^{(0)} = 0.36$ and $\Sigma_{\pi N}$.
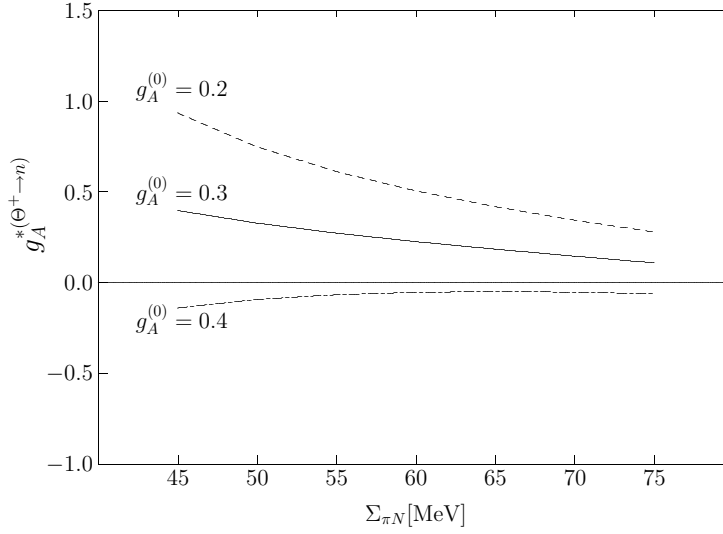
Fig. 2.  The transition axial-vector coupling constant for $\Theta^+ \to K^+ n$ as a function of $\Sigma_{\pi N}$. The solid curve denotes that with $g_A^{(0)} = 0.3$, while the dashed and dot-dashed ones represent that with $g_A^{(0)} = 0.2,\ 0.4$, respectively.

| $\Gamma_{\Theta KN}^{\text{(total)}}$ | Input $g_A^{(0)}$ | | | |
|---|---|---|---|---|
| $\Sigma_{\pi N}$[MeV] | 0.28 | 0.32 | 0.36 | 0.40 |
| 50 | 22.25 | 7.82 | 0.76 | 1.10 |
| 60 | 10.45 | 3.82 | 0.46 | 0.36 |
| 70 | 4.54 | 1.50 | 0.10 | 0.35 |

Table II.  The decay width of $\Theta^+ \to KN$ determined with $g_A^{(0)}$ varied from 0.28 to 0.40. The $\Sigma_{\pi N}$ is varied from 45 to 75 MeV.

Figure 3 shows the results of the total decay width of the $\Theta^+ \to KN$ as a function of $g_A^{(0)}$ and $\Sigma_{\pi N}$ in a three dimensional plot. As shown in Fig. 3, the minimum of the total decay width $\Gamma_{\Theta KN}$ is found to be around $g_A^{(0)} = 0.37$ with $\Sigma_{\pi N} = 65$ MeV. Thus, using this interrelation among $g_A^{(0)}$, $\Sigma_{\pi N}$, and $\Gamma_{\Theta KN}$, we can consider a certain window for their values within the present analysis.

Figure 4 shows the window for the total decay width of the $\Theta^+ \to KN$, given $g_A^{(0)}$ and $\Sigma_{\pi N}$. The shaded rectangle indicates the area where one has generally accepted experimental values of $g_A^{(0)}$ and $\Sigma_{\pi N}$, i.e. $0.3 - 0.4$ and $65 - 75$ MeV, respectively, and simultaneously a $\Gamma_{\Theta KN} \leq 1$ MeV. It is of great interest to see that the range of $g_A^{(0)}$ is compatible with a theoretical investigation,[21] based on the $\chi$QSM,and on the COMPASS and HERMES measurements of the deuteron spin-dependent structure function.[22]–[24]  It is worthwhile to mention that the values of $g_A^{(0)}$ in the present analysis is almost the same as theoretical results within the $\chi$QSM.[25],[26] The range of $\Sigma_{\pi N}$ given above is consistent with a recent analysis.[27]  If one interprets the result of the DIANA collaboration[5] as identification of the $\Theta^+$, namely the formation of a narrow $pK^0$ peak with mass of $1537 \pm 2$ MeV$/c^2$ and width of $\Gamma = 0.36 \pm 0.11$ MeV
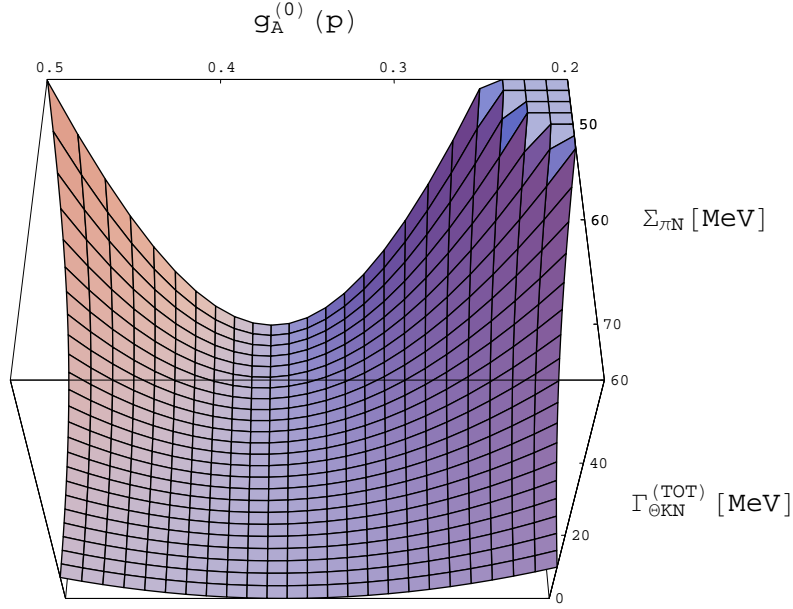
$$g_A^{(0)} \, (\mathrm{p})$$

Fig. 3.  The total decay width of $\Theta^+ \rightarrow KN$ as a function of $g_A^{(0)}$ and $\Sigma_{\pi N}$.

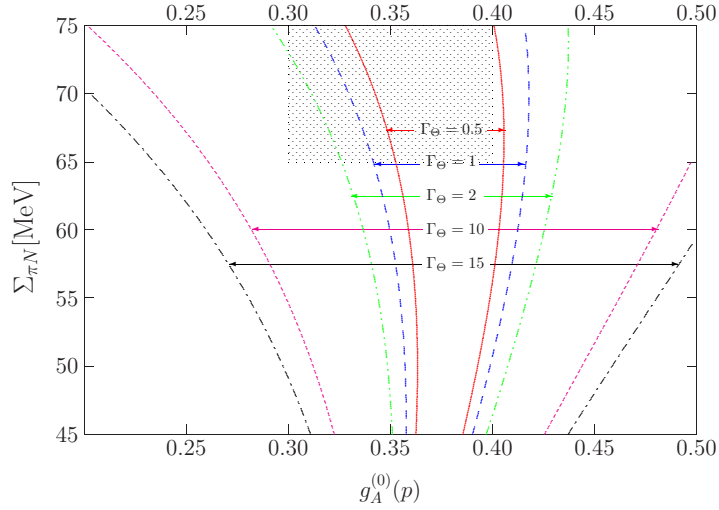in the $K^+ n \rightarrow K^0 p$ transition, then that result is inside the shaded area of Fig. 4.

Fig. 4.  The total decay width of $\Theta^+ \rightarrow KN$ in units of MeV as a function of $g_A^{(0)}$ and $\Sigma_{\pi N}$. The shaded area denotes the ranges of $g_A^{(0)}$: $0.3 - 0.4$ and of $\Sigma_{\pi N}$: $65 - 75$ MeV.

## §4. Summary and Conclusions

In the present talk, we have reported the recent investigation on the magnetic transitions and axial-vector transitions from the baryon antidecuplet to the nucleons, emphasizing, in particular, the $\Theta^+$ baryon and the new $N^*(1675)$ resonance from the GRAAL and Tohoku LNS experiments. We used the the *model-independent approach* within the framework of the chiral quark-soliton model, thereby taking explicit SU(3)-symmetry breaking into account. The parameters in the model are all fixed by the known experimental data, i.e. octet magnetic moments, hyperon semileptonic decay constants, singlet axial-vector constant, octet masses, and the mass of the $\Theta^+$, where the residual freedom is parametrized by the pion-nucleon sigma term, $\Sigma_{\pi N}$. The results for $\mu_{N\Delta}$ and $\mu_{\Lambda^0 \Sigma^0}$ are well reproduced, compared to the experimental and empirical data. The transition magnetic moment $\mu_{\Sigma^- \Sigma^{*-}}$, which has only a non-zero value due to explicit SU(3)-symmetry breaking, is found to be below its upper bound extracted from the SELEX data.[20]

The transition magnetic moment $\mu_{nn^*_{\overline{10}}}$ turns out to be rather sensitive to the value of $\Sigma_{\pi N}$ due to the constructive interference of the parameters $w_1(\Sigma_{\pi N})$ and $w_1(\Sigma_{\pi N})$. The value of the $\mu_{pp^*_{\overline{10}}}$ is rather small in comparison with that of the $\mu_{nn^*_{\overline{10}}}$ due to the explicit SU(3)-symmetry breaking. As a result, the present predictions for the transition magnetic moments $\mu_{pp^*_{\overline{10}}}$ and $\mu_{nn^*_{\overline{10}}}$ are consistent with the recent GRAAL data on $\gamma p \to \eta p$ and $\gamma n \to \eta n$. This supports the view that the new resonance $N^*(1675)$ corresponds to a neutron-like member of the pentaquark baryon antidecuplet.

We also presented the recent results of the transition axial-vector coupling constant for the $\Theta^+ \to K^+ n$, $g_A^{*(\Theta \to n)}$ and the total decay width of the $\Theta \to KN$. We showed that the $g_A^{*(\Theta \to n)}$ decreases as $g_A^{(0)}$ increases. It also depends on the $\pi N$ sigma term in such a way that it is getting smaller as the $\Sigma_{\pi N}$ increases. It was also shown that the $g_A^{*(\Theta \to n)}$ turns out to be negative around $g_A^{(0)} \simeq 0.37$.

The total width $\Gamma_{\Theta KN}$ of the $\Theta^+ \to KN$ decay was finally investigated. Since it is proportional to the square of the transition axial-vector constant $g_A^{*(\Theta \to n)}$, it is rather sensitive to the $g_A^{*(\Theta \to n)}$. The $\Gamma_{\Theta KN}$ is getting suppressed as the singlet axial-vector constant $g_A^{(0)}$ increases. However, since the $g_A^{*(\Theta \to n)}$ becomes negative around 0.37, the $\Gamma_{\Theta KN}$ starts to increase around 0.37. As a result, the total decay width $\Gamma_{\Theta KN}$ turns out to be smaller than 1 MeV for values of the $g_A^{(0)}$ and $\Sigma_{\pi N}$ larger than 0.31 and 65 MeV, respectively.

According to the analysis of the total width $\Gamma_{\Theta KN}$, we draw a conclusion as follows: The known data of semileptonic decays combined with $0.3 \leq g_A^{(0)} \leq 0.4$ and $\Sigma_{\pi N} \geq 65$ MeV is compatible with the existence of a $\Theta^+$ pentaquark having a small width of the total decay $\Theta^+ \to KN$, that is $\Gamma_{\Theta KN} \leq 1$ MeV.

## Acknowledgments

## References

1) L. M. Brown and Y. Nambu, Scientific American, December 1998, 96 (1998).
2) T. Nakano *et al.* [LEPS Collaboration], Phys. Rev. Lett. **91**, 012002 (2003).
3) D. Diakonov, V. Petrov and M. V. Polyakov, Z. Phys. **A359** (1997) 305.
4) M. Battaglieri *et al.* [CLAS Collaboration], Phys. Rev. Lett. **96**, 042001 (2006).
5) V. V. Barmin *et al.* [DIANA Collaboration], Phys. Atom. Nucl. **70**, 35 (2007).
6) T. Hotta [LEPS Collaboration], Acta Phys. Polon. B **36**, 2173 (2005).
7) K. Miwa *et al.* [KEK-PS E522 Collaboration], arXiv:nucl-ex/0601032.
8) T. Nakano, a talk presented in the Workshop on Hadronic and Nuclear Physics 2007 (HNP 2007), http://hadron.phys.pusan.ac.kr∼hnp07/.
9) V. Kuznetsov [GRAAL Collaboration], arXiv:hep-ex/0409032.
10) V. Kuznetsov [GRAAL Collaboration], arXiv:hep-ex/0606065.
11) J. Kasagi, "*Observation of Narrow Resonance in the $d(\gamma, \eta)$ Reaction at $E_\gamma sim 1000$ MeV: A Candidate for the Anti-decuplet N\* Produced in Photo-Neutron Excitation*", in this proceedings.
12) M. V. Polyakov and A. Rathke, Eur. Phys. J. A **18**, 691 (2003).
13) H.-Ch. Kim, M. Polyakov, M. Praszałowicz, G. S. Yang and K. Goeke, Phys. Rev. D **71**, 094023 (2005).
14) K. S. Choi, S. i. Nam, A. Hosaka and H.-Ch. Kim, Phys. Lett. B **636**, 253 (2006).
15) A. Fix, L. Tiator and M. V. Polyakov, arXiv:nucl-th/0702034.
16) Y. Azimov, V. Kuznetsov, M. V. Polyakov and I. Strakovsky, Eur. Phys. J. A **25**, 325 (2005).
17) G. S. Yang, H. C. Kim and K. Goeke, arXiv:hep-ph/0701168, accepted for publication in Phys.Rev. D.
18) G. S. Adkins and C. R. Nappi, Nucl. Phys. B **249**, 507 (1985).
19) G. S. Yang, H.-Ch. Kim, M. Praszalowicz and K. Goeke, Phys. Rev. D **70**, 114002 (2004).
20) V. V. Molchanov *et al.* [SELEX Collaboration], Phys. Lett. B **590**, 161 (2004).
21) M. Wakamatsu, Phys. Lett. B **646**, 24 (2007).
22) E. S. Ageev *et al.* [COMPASS Collaboration], Phys. Lett. B **612**, 154 (2005).
23) V. Y. Alexakhin *et al.* [COMPASS Collaboration], arXiv:hep-ex/0609038.
24) A. Airapetian *et al.* [HERMES Collaboration], arXiv:hep-ex/0609039.
25) M. Wakamatsu and T. Watabe, Phys. Rev. D **62**, 054009 (2000).
26) A. Silva, H. C. Kim, D. Urbano and K. Goeke, Phys. Rev. D **72**, 094011 (2005).
27) P. Schweitzer, Eur. Phys. J. A **22** (2004) 89.